# Toward a conceptual model of floodplain water table response

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Received 25 August 2003; revised 16 June 2004; accepted 13 October 2004; published 18 December 2004.

[1] Hydrological processes operating within floodplains in temperate midlatitudes have significant implications for water management by controlling pollutant transfer between the catchment and the fluvial system. However, there is a lack of relevant high-resolution data from which the dynamics of floodplain hydrology during flood events can be inferred. A detailed analysis of water table fluctuations during flood events within a typical European lowland floodplain system (River Severn, United Kingdom) is presented. Data collected hourly along two 120-meter-long transects, each comprising four piezometers, plus one river stage sensor, are analyzed for the winter season 1998–1999 using correlation analysis, hysteresis curves, and water table maps. The objective is to develop a conceptual model that provides mechanistic understanding of floodplain water table response during flood events. River stage is shown to be the principal driver of water table fluctuations. Piezometers with similar water table response are identified; their consistent pattern of response in different flood events is attributed to sedimentary and morphological controls on the floodplain and adjoining hillslopes. Deviations from the general pattern are a function of low antecedent soil moisture, which is only a significant factor at the beginning of the winter season, when the floodplain is initially dry. Our conceptual model adopts a kinematic wave process whereby river stage change induces rapid responses of the water table over many tens of meters across the floodplain, associated with flux velocities several orders of magnitude higher than would be expected for Darcian flow. The occurrence of a groundwater ridge within the floodplain dams hillslope drainage and causes the water table to rise at the back of the floodplain. The disappearance of the groundwater ridge during the recession reestablishes hillslope flow into the floodplain, resulting in significant three-dimensional hydraulic gradients directed both perpendicular and parallel to the channel axis. *INDEX TERMS:* 1890 Hydrology: Wetlands; 1860 Hydrology: Runoff and streamflow; 1829 Hydrology: Groundwater hydrology; 1866 Hydrology: Soil moisture; *KEYWORDS:* channel-acquifer interactions, floodplain hydrology, hysteresis, piston flow, three-dimensional flow, water table

**Citation:** Jung, M., T. P. Burt, and P. D. Bates (2004), Toward a conceptual model of floodplain water table response, *Water Resour. Res.*, *40*, W12409, doi:10.1029/2003WR002619.

## 1. Introduction

[2] Floodplains represent zones of important geomorphological, ecological, and hydrological processes that control the linkage between hillslope and channel domains in lowland environments. In this context, floodplain hydrology is of great significance to pathways and dynamics of pollutant transport [e.g., *Hill*, 1990, 1997; *Haycock et al.*, 1997], ecosystem functioning [*Meyer and Edwards*, 1990; *Smock et al.*, 1992], habitat diversity and connectivity [e.g., *Forman and Gordon*, 1986; *Junk*, 1997, 1999; *Huggenberger et al.*, 1998], and the downstream propagation of flood waves [e.g., *Kondolf et al.*, 1987; *Hunt*, 1990; *Stewart et al.*, 1999]. In humid temperate environments, the floodplain aquifer receives water from local precipitation, hillslope runoff, and the channel (during floods) and then stores, redistributes and eventually releases the water to the river under base flow conditions [*Mertes*, 1997; *Woessner*, 2000]. Besides these variable inputs and antecedent moisture conditions, water table fluctuations within the floodplain have been found to be highly dependent on the morphology [e.g., *Mertes*, 1997], material properties [e.g., *Gillham*, 1984] and internal structure of the floodplain sediments, the latter frequently providing paths of preferential flow [e.g., *Poole et al.*, 2002; *Burt et al.*, 2002b]. Despite considerable research on the effect of bank storage on flood hydrographs [e.g., *Kondolf et al.*, 1987; *Hunt*, 1990], groundwater recharge of alluvial aquifers [*Winter*, 1995], and more recently on channel-aquifer interactions in the hyporheic zone [e.g., *Stanford and Ward*, 1988; *Dahm and Valett*, 1996], very little has been published about the complex hydrological interactions between subsurface hillslope runoff, floodplain groundwater, and river floodwater on a high-resolution event basis. One reason for this is a lack of high-resolution data (both spatial and temporal), but such data are essential to an understanding of floodplain

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0043-1397/04/2003WR002619$09.00

hydrology and thereby several other aspects of floodplain function. For example, denitrification and other nitrogen cycling processes will be strongly dependent on hydrological fluctuations within the floodplain [*Burt et al.*, 2002a] as denitrification reactions optimally require anaerobic saturated conditions. Saturation levels and water fluxes also impact flow paths, residence times and the mobilization of potential contaminants within the floodplain; there is a clear correlation between saturation levels, hydraulic conductivity and pollutant transport rates [*Claxton et al.*, 2003]. During floods, higher water tables on the floodplain may also lead to greater connectivity between hillslopes and channels and act as a control on the movement of nutrients and genetic material between terrestrial and aquatic ecosystems. Hence a better understanding of the dynamics of floodplain hydrology is a key step toward the better management of lowland floodplain environments.

[3] A field experiment to investigate water table fluctuations was set up on the floodplain of the River Severn, Shropshire, United Kingdom; substantial hydrological interactions between the river, the floodplain and the adjacent hillslopes have been documented at this site [*Stewart et al.*, 1999]. The classic model for such interactions is the so-called "bank storage" effect [*Pinder and Sauer*, 1971, Figure 1]. Under base flow conditions, groundwater discharges from the floodplain into the river, but during a flood, when the water level in the channel rises above the water table in the floodplain, this reverses the hydraulic gradient and induces flow from the channel into the floodplain. After the flood, the river level falls and a streamward hydraulic gradient is again established. At first, floodplain water flows in both directions, but eventually all floodplain flow is toward the river. Hence the bank storage model envisages floodplain flow processes as being predominantly two-dimensional, perpendicular to the river.

[4] Starting from this conceptual basis, *Bates et al.* [2000] combined field data with two-dimensional vertically aligned numerical modeling to study river-floodplain-hillslope interactions along a cross-floodplain transect for two over-bank events at the River Severn field site. The results showed that an extensive hyporheic zone and a groundwater ridge formed within the floodplain during over-bank flooding, with a strong water table gradient directed toward the hillslope-floodplain boundary. River stage and floodplain water levels rose and fell by up to 5 m during each event, implying that a lateral flux of water across the floodplain, perpendicular to the channel, was likely to be the dominant flow process occurring during a flood event, in accordance with the classic bank storage model. By contrast, up- and down-valley water table gradients were comparatively low during a flood event, indicating that a three-dimensional flow pattern (with significant water table gradients in both the cross-floodplain and down-valley directions) was unlikely to exist during a flood and that a two-dimensional modeling approach was justified.

[5] *Bates et al.* [2000] found that a groundwater ridge developed within the floodplain because, while the water table in the near-channel zone rose near-synchronously with the rising river stage, the water table at the base of the hillslope did not respond until much later in the event, when subsurface storm flow on the adjacent hillslope, in response to local rainfall, reached the hillslope-floodplain boundary. In effect, the water table level beneath the inundated floodplain rapidly rose to the surface, but in the noninundated zone at the base of the hillslope, the water level did not rise until much later. As a result, for most of the flood, water table gradient was effectively zero across most of the floodplain but there was a high hydraulic gradient near the back of the floodplain toward the base of the hillslope. Model results indicated high flow velocities directed toward the hillslope as the inundation front approached the hillslope/floodplain junction. The arrival of the groundwater ridge at the floodplain edge acted as a barrier for hillslope drainage, temporarily "switching off" subsurface hillslope inputs to the floodplain, a condition that, depending on the event dynamics, can prevail for up to 10 days according to the results of *Claxton et al.* [2003]. The two-dimensional model was found to perform well around the flood peak but was much less successful during the rising and recession limbs. The authors nevertheless concluded that floodplain groundwater flows were dominated by cross-floodplain fluxes approximately perpendicular to the river during a flood event. However, they noted that, at the beginning and end of a flood event, the down-valley hydraulic gradient could become comparable to the lateral, cross-floodplain gradient and that a more three-dimensional flow field could potentially become established with both lateral and down-valley fluxes becoming significant within the alluvial sediments. Here, we here adopt the same terminology as *Bates et al.* [2000] and the classic bank storage model, with the cross-floodplain and vertical directions being referred to as dimensions 1 and 2, and the down-valley direction being dimension 3. A two-dimensional flow is therefore considered to be one where the flux direction is across the floodplain, perpendicular to the channel.

[6] On the basis of the model results of *Bates et al.* [2000], *Burt et al.* [2002b] reconsidered the piezometer data of both flood events modeled by *Bates et al.* [2000] and, additionally, included three smaller in-bank events in their interpretation of water table fluctuations. It was found that a similar groundwater ridge also forms during in-bank events. *Burt et al.* [2002b] also showed the existence of flow paths that were predominantly parallel to the river during the recession period. The development of such a three-dimensional flow pattern (with significant cross-floodplain and down-valley fluxes) was attributed to local topographic features of the floodplain and the hillslope, determining different up-slope contributing areas of subsurface hillslope discharge. The water tables influenced by a hillslope hollow revealed enhanced groundwater levels and therefore the formation of a [*Burt et al.*, 2002b, p. 18] "dome of groundwater...with flow fanning out, not only across the floodplain toward the river, but also sideways, down-valley, and, indeed, up-valley." The existence of both lateral and down-valley flows of floodplain groundwater, generated by locally stronger hillslope runoff during the recession period, enabled *Burt et al.* [2002b, p. 18] to conclude that "a full three-dimensional approach becomes essential" in contrast to the classic bank storage model.

## 2. Aims and Objectives

[7] The aim of this paper is to provide a detailed analysis and description of floodplain water table response during

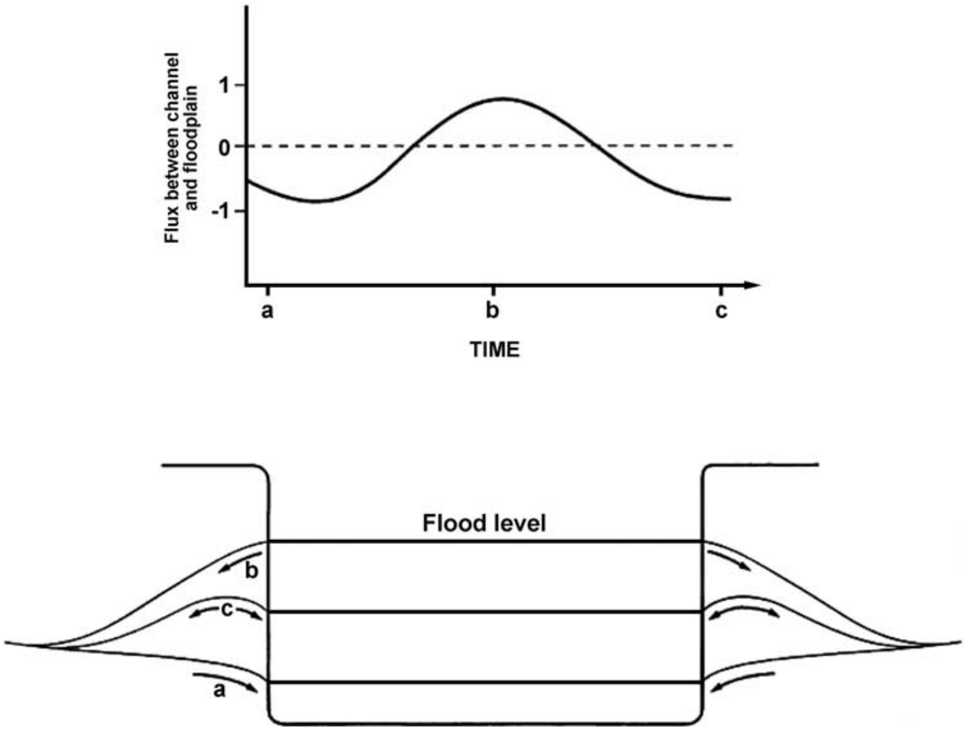


**Figure 1.** Scheme of the bank storage process. The upper panel presents the water balance of the floodplain; the lower panel shows an idealized cross section of the river with the adjoining aquifer. At time "a" the river is receiving base flow; at time "b" a flood peak is passing and flow is induced into the banks; at time "c" the peak has passed and the bank storage wedge is draining [modified from *Dingman*, 1994].

flood events. The results are used to derive a conceptual three-dimensional model of floodplain hydrology, which emphasises linkages with both adjacent hillslopes and the river channel. This is achieved by identifying characteristic, recurrent spatial and temporal patterns of water table response within the floodplain and their controlling factors. First, we locate and characterize spatial response units within the floodplain, making it possible to reduce the dimensionality of the data to a few sensors, each of which is representative of the identified units and which together characterize the system behavior. Next, we examine whether deviating patterns of water table response during different flood events can be identified, based on the behavior of representative sensors. We then identify characteristic patterns of water table response and seek to explain them in relation to the main controlling factors: river stage, hillslope discharge and antecedent conditions. Finally, the results are used to propose a conceptual model of floodplain water table response.

## 3. Study Area and Sampling Strategy

[8] The field site is situated on a straight channel section on the left bank of the River Severn near the village of Leighton, Shropshire, United Kingdom. The total floodplain here is ~1 km wide with a ~45 m wide main channel. The field site is located approximately midway along the Severn at ~40 m above sea level; the basin area is ~3717 km$^2$ and drains eastward from the Welsh uplands which rise to ~600 m above sea level. Bankfull discharge at Leighton is ~180 m$^3$ s$^{-1}$ with the largest floods peaks exceeding 450 m$^3$ s$^{-1}$. Here, the left-bank floodplain is only ~120 m wide and is bounded by a ~70 m high, ~25° slope consisting of the remnants of one or more alluvial terraces and colluvial hillslope material. The slope comprises two distinct geomorphological features: a hollow (upslope contributing area ~2 ha) with plan concavity and convergent flow, and an adjacent neighboring spur (upslope contributing area ~150 m$^2$) with a convex profile and divergent flow. The spur feature is ~5 m wide and extends back to the top of the terrace rampart approximately 30m back from the edge of the floodplain. The hollow drains a much larger wedge-shaped area extending back to the local watershed. The major geomorphological features on the floodplain are the extension of the hillslope hollow on to the floodplain toward the southeast as a shallow depression, and a lower area near and subparallel to the channel. A coring survey revealed a relatively simple subsurface stratigraphy across the floodplain. A gravel layer of unknown thickness is evident at depths ranging from 2.4 to 5.5 m, overlain by sandy-clay material. The saturated hydraulic conductivity of both stratigraphic units was found by falling head well tests to be of the same order of magnitude, $2.54 \times 10^{-6}$ m s$^{-1}$ and $1.56 \times 10^{-6}$ m s$^{-1}$ respectively (Figure 1).

[9] Two 120 m transects were installed to monitor soil water pressure across the full width of the left bank floodplain at Leighton (see Figure 2). The piezometers furthest from the river in each transect were placed several meters upslope of the break in slope at the edge of the floodplain in order to capture the net hillslope flux to the

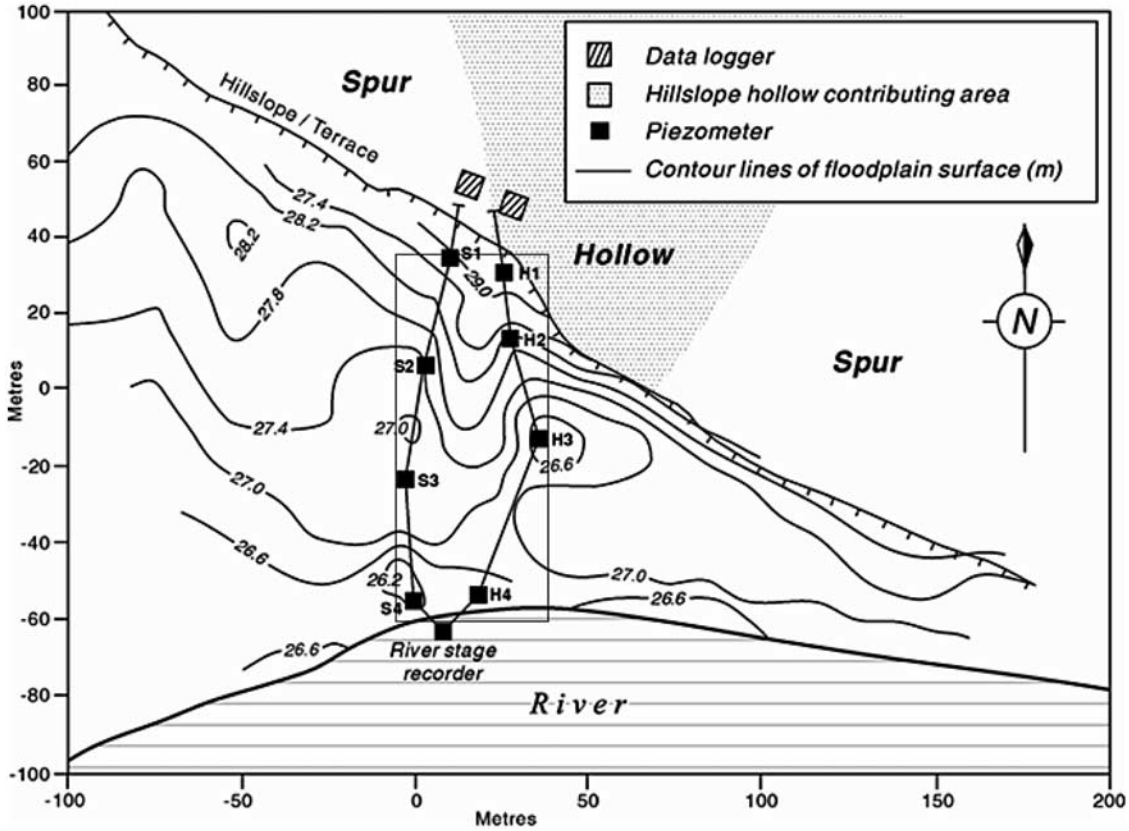


**Figure 2.** Map of the study site. The spur and hollow transects are shown by the lines passing through the sensors. The rectangle indicates the area for which surface maps of the water table were produced.

floodplain at this point. One transect runs from the end point of the hillslope spur to the channel, while the other begins at the point where the hillslope hollow discharges into the floodplain and continues along the depression before running across the floodplain to the channel. Piezometers are labeled numerically from the hillslope to the channel. Thus transect S (Spur) has four sensors (S1–S4) installed from the base of the hillslope (S1) and across the floodplain, with S4 being set ~3 m back from the channel bank. Transect H (Hillslope) has three sensors (H1, H2 and H3) within the floodplain extension of the hollow and a further sensor (H4) close to the river bank. There was also continuous measurement of river stage and precipitation. All sensors were connected to data loggers. Measurements were taken every 15 min and stored as hourly averages. Potential errors of the piezometric data are of the order of ±10 cm.

## 4. Methods

[10] We analyze data from four over-bank flood events (event A, D, E and G) that occurred in winter 1998–1999 (Figure 3). Unless otherwise stated, all available piezometer data from these events are used for the analysis of water table response. To study whether memory effects of previous events impact upon water table response, three in-bank events (event B, C and F) were included, which together with over-bank events D and E, form an event sequence (B, C, D, E and F).

[11] Piezometer interrelationships were explored by correlation analysis using SPSS 8.0. The results of the correlation analysis were used to classify the piezometers into groups of sensors with similar behavior, making it possible to reduce the complexity of various piezometer time series to a few representative sensors. Scatterplots of representative sensors were then produced for visual interpretation; these contain the necessary information required to describe the system behavior and were used to identify recurring water table patterns during flood events. Scatterplots were also used to generate hysteresis curves showing the covariation between piezometers and river stage.

[12] To visualize recurring water table patterns, we produced water table maps for two selected events; these provide a representative picture of water table changes during flood events at the study site for the time period addressed. Water table mapping was performed with the SURFER 7.0 visualization package using kriging with a simple linear variogram. For simplicity, the interpolated water table was calculated for a rectangular bounding box. Some uncertainty is associated with a lack of information between the piezometer transects, which might be of significance since there are marked changes in the surface topography of the floodplain. Therefore the maps cannot be regarded as an exact representation of the water table, but the general pattern is likely to be reliable, given the relatively smooth and low-gradient spatial patterns of water table response. Twelve maps were produced for both, the first and last over-bank events of the season (event A and G, Figure 3). All maps are based on full resolution with 11 data points, four along each transect plus three along the river, except those labeled with an asterisk, where no data for

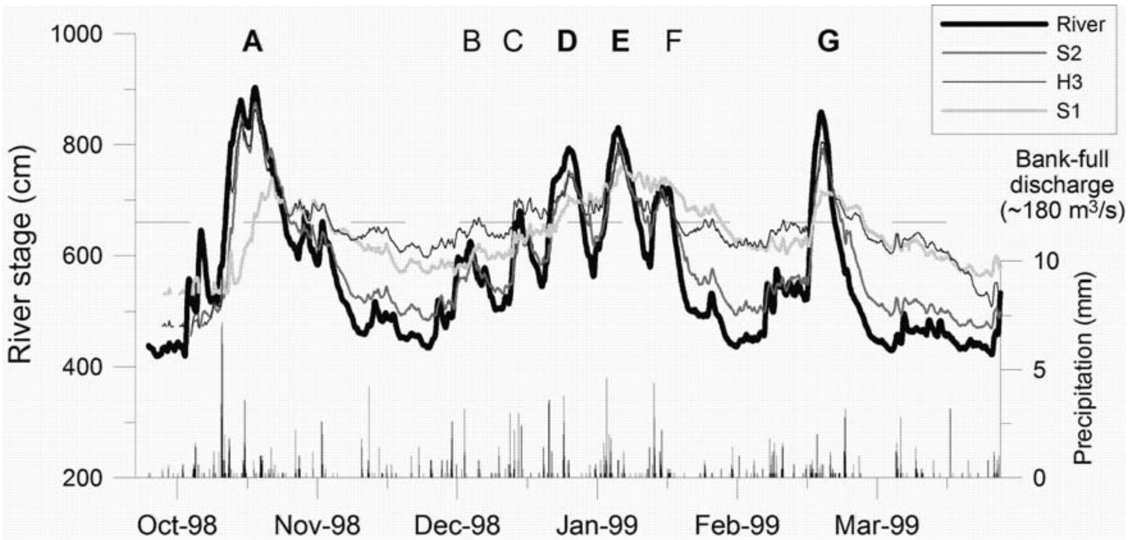


**Figure 3.** River stage and hydraulic head for selected sensors during the considered winter period 1998–1999, capturing the behavior of the water table. While high water tables are maintained at S1 and H3 after flood events, the water table at S2 declines approximately in parallel with river stage. Each of the sensors will be shown to be representative for certain floodplain units. Events considered in this paper are labeled from A to G: letters in bold represent over-bank events. We consider event F as in-bank since only relatively localized flooding near the river banks occurred.

piezometer H1 were available. Since a few piezometers sometimes failed to operate in the early rising limb or late recession period as the water table was below the datum level of the piezometer, we chose to avoid these stages. Thus some bias is introduced in the choice of the point in time for which maps were produced.

## 5. Results

### 5.1. Piezometer Intercorrelations

[13] A matrix of squared correlation coefficient ($R^2$) values for all piezometer pairs including river stage is provided in Table 1. Two distinct groups of piezometers appear. First, the piezometers S1, H1 and H2 near the floodplain-hillslope border are interrelated but show no significant correlation with the other floodplain piezometers or river stage. Second, all remaining piezometers (S4, S3, S2, and H4) exhibit strong intercorrelations and are all strongly correlated with river stage. This group can further be divided into two groups of piezometers with very strong intercorrelations ($R^2$ values above 0.9). The first group includes the river bank piezometers S4 and H4 and river stage, while the second group is located along the spur transect (S3–S2 and S4–S2. In addition, H3 must be

**Table 1.** Matrix With $R^2$ Values for Each Piezometer Pair[a]

| | River | H4 | S4 | S2 | S3 | H3 | H1 | S1 | H2 |
|---|---|---|---|---|---|---|---|---|---|
| River | 1.00 | ***0.94*** | ***0.96*** | **0.83** | **0.76** | **0.73** | 0.16 | 0.05 | 0.05 |
| | 1775 | 1602 | 1775 | 1775 | 1584 | 1775 | 1407 | 1754 | 1663 |
| H4 | | 1.00 | ***0.98*** | **0.89** | **0.88** | **0.79** | 0.20 | 0.04 | 0.02 |
| | | 1602 | 1602 | 1602 | 1570 | 1602 | 1386 | 1586 | 1495 |
| S4 | | | 1.00 | ***0.93*** | **0.88** | **0.83** | 0.22 | 0.10 | 0.08 |
| | | | 1775 | 1775 | 1584 | 1775 | 1407 | 1754 | 1663 |
| S2 | | | | 1.00 | ***0.94*** | **0.86** | 0.31 | 0.21 | 0.12 |
| | | | | 1775 | 1584 | 1775 | 1407 | 1754 | 1663 |
| S3 | | | | | 1.00 | **0.79** | 0.31 | 0.10 | 0.06 |
| | | | | | 1584 | 1584 | 1389 | 1584 | 1509 |
| H3 | | | | | | 1.00 | 0.17 | 0.16 | 0.08 |
| | | | | | | 1775 | 1407 | 1754 | 1663 |
| H1 | | | | | | | 1.00 | **0.88** | **0.63** |
| | | | | | | | 1407 | 1407 | 1407 |
| S1 | | | | | | | | 1.00 | **0.73** |
| | | | | | | | | 1754 | 1663 |
| H2 | | | | | | | | | 1.00 |
| | | | | | | | | | 1663 |

[a]Data from flood events A, D, E, and G were included in the analysis. Values above 0.9 are in bold and italic; values between 0.6 and 0.9 are in bold. The number below each $R^2$ value refers to the number of available data points (i.e., hours) since not all sensors were always working at the same time.

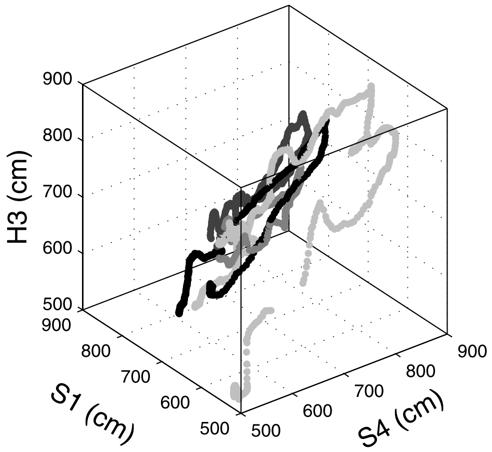


**Figure 4.** System state of the floodplain groundwater table, defined by the constellation of the water table at the piezometers S4, S1, and H3, representing the river banks and spur, hillslope, and floodplain hollow group, respectively. Data from all four over-bank (A, D, E, G) events are shown in chronological order from light gray to black.

considered separately because it indicates the behavior of the lower hillslope hollow.

### 5.2. Repetition of Water Table Behavior

[14] Given the high correlations between specific groups of piezometers, S1, S4 and H3 are sufficient to visualize the behavior of the water table for the different events in three-dimensions (Figure 4). The sensors chosen represent the hillslope piezometers that respond independently of river stage, those piezometers strongly correlated with river stage, and the floodplain hollow with its own response pattern. While the behavior of the water table is similar for events D, E and G, the rising limb of event A in autumn 1998 deviates significantly from the general pattern. Therefore we chose events A and G to map changing patterns of water table response with event G being also representative of events D and E.

### 5.3. Water Table Maps

[15] The preevent conditions of event A in autumn 1998 are characterized by a comparatively low and horizontal piezometric surface at ca. 520 cm above datum without significant gradients within the water table or toward the river (Figure 5a). When the river starts to rise, the water table rises accordingly as an essentially planar horizontal surface by 70 cm within 2 days (Figure 5b) until inundation occurs in the near-river area and along the floodplain hollow, causing the water table there to rise by more than a meter within 1 day (Figure 5c). Now, a groundwater ridge or dome (i.e., with a clearly three-dimensional form) develops with downward gradients of ~4% directed to the spur transect and the hillslope-floodplain boundary. By day 4, the inundation front reaches piezometer S3, which rises rapidly by 2 meters within 4 hours due to the large infiltration flux and a steep water table gradient (~8%) toward the hillslope-floodplain border develops (Figure 5e). At this point, the lateral water table gradient is much greater than the up- or down-valley gradients, and the flow pattern can essentially be described as two-dimensional across the floodplain. This pattern persists for ~5 days, associated with rising water tables from 550 cm to 740 cm at the foot of the hillslope and hence decreasing lateral hydraulic gradients, until the recession commences (Figure 5f) after ~9 days from the beginning of the event. During the early recession (Figures 5g–5i), the water table falls in line with river stage by ~35 cm/day and therefore exhibits a planar shape again, although a significant depression in the piezometric surface near piezometer H2 is indicated on the maps (Figures 5g and 5h). Whether this represents a problem with the sensor or is real remains uncertain, but a measurement error seems likely on this occasion. This effect will therefore not be discussed in great depth later on. During the later recession (Figures 5j–5l), when standing water is no longer present on the floodplain, the water table pattern undergoes a transition from the classic two-dimensional bank storage model condition with flow gradients of ~2% directed toward the channel (Figure 5j), to a three-dimensional pattern caused by high water tables (~650 cm) at the floodplain hollow (H3) and the hillslope piezometers, with gradients of ~2 to 3% from the floodplain hollow toward the spur transect and the river (Figures 5k and 5l). The three-dimensional pattern is established after ~3 weeks from the start of the rising limb and ~10 days after the flood peak. It persists for the entire winter season, except during high-discharge events, and may be regarded as the "normal" winter condition at this site.

[16] The sequence of water table patterns over the course of event G in February and March 1999 event is only slightly different. The preevent water table shows base flow conditions with the familiar groundwater dome within the floodplain hollow at H3 (Figure 6a). The rising river causes the spur piezometers S3 and S2 to rise synchronously by ~70 cm within 2 days, compensating the three-dimensional nature of the gradient field and eventually forming a planar horizontal surface (Figures 6b–6d), similar to the pattern of event A at this stage (Figure 5b). In the following period (Figures 6e–6g), the water table across the floodplain continues to rise nearly synchronously with the river by ~80 cm/day. Hence there is no significant asymmetric water table between hollow and spur transect as during event A in autumn 1998 (Figure 5c and 5d). In general, the gradients toward the hillslope associated with the groundwater ridge are ~3% in comparison to 8% during event A (Figure 5e), although the depression at H2 develops repeatedly (Figures 6f and 6g). The patterns of water table fluctuations during the recession period (Figures 6h–6l) are essentially identical to event A (Figures 5h–5l).

[17] So far, we have identified spatial units of water table response within the floodplain, which respond similarly during flood events. We have also shown that the water table fluctuations during flood events at this site follow a recurring pattern, except for the rising limb of event A, which deviates from the pattern of the remaining events. The next sections explore the dynamics of the water table more closely by examining the response of piezometers to river stage and hillslope runoff.

### 5.4. Response of Piezometers to River Stage

[18] Here we use S4, S2, H3 and S1 as representative sensors of the river banks, spur, hollow and hillslope group respectively to reduce the dimensionality of the data. The chosen sensors are those which operated continuously

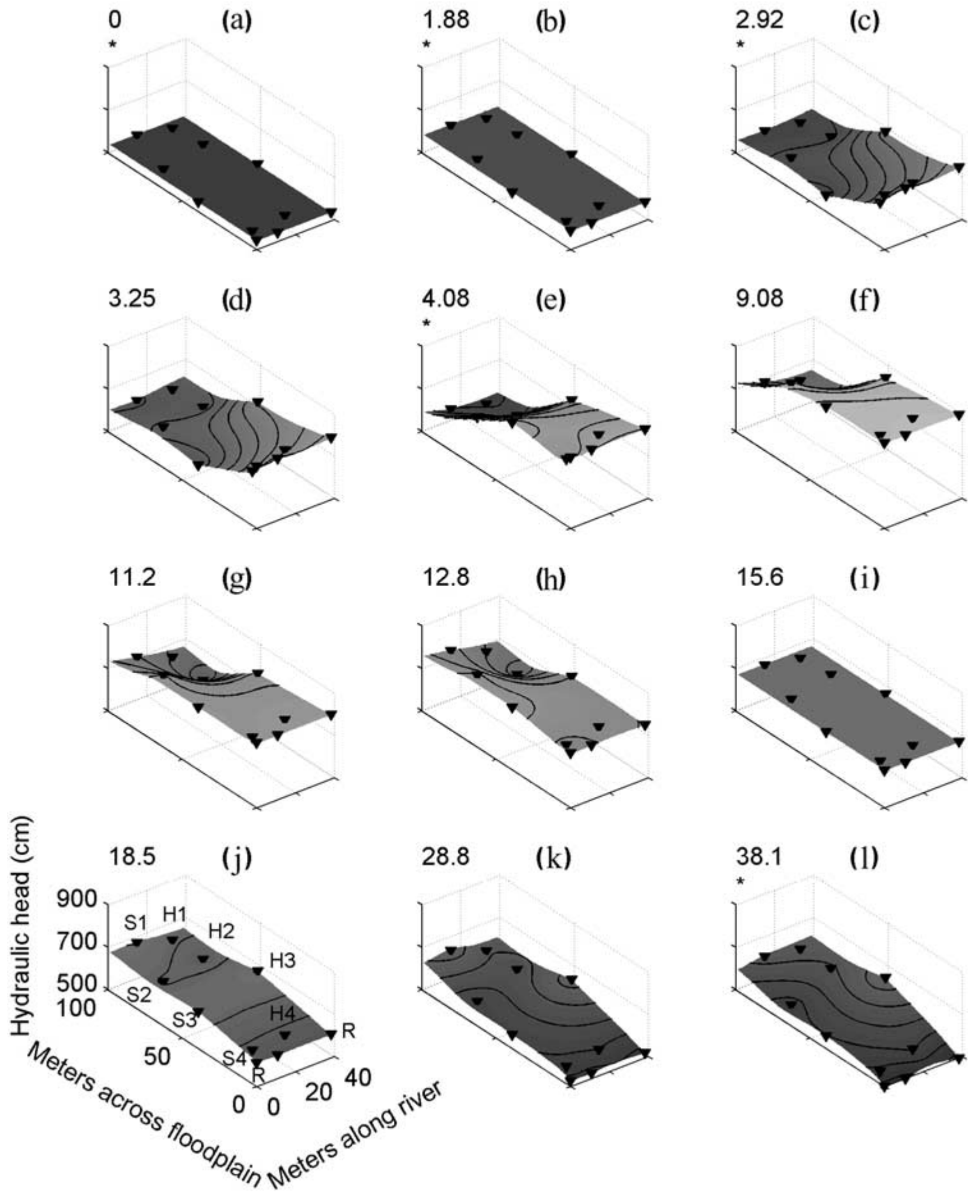


**Figure 5.** Sequence of water table maps over the course of event A in autumn 1998. The number of days since the start of the rising period is given at the top left of each map. Where an asterisk is indicated, no data for H1 were available for the interpolation.

within each group (see Table 1; number of available data points for correlations). Figure 7 presents river stage – water table hysteresis plots for the piezometers S1, S2, H3, and S4, which represent the hillslope group (S1, H1, H2), the spur transect group (S2, S3), the floodplain hollow (H3) and the river bank group (H4, S4), respectively.

[19] The riverbank piezometers show a synchronous and essentially identical behavior to river stage since all data points are aligned along the $x = y$ line. The hysteresis plots for the four events are remarkably similar suggesting very little difference in the water table response between events. For all recession periods, the response of the river bank piezometers (H4, S4) can also be regarded as identical to river stage since the data points overlay each other. The narrow shape of the hysteresis curves also implies only minor differences in the water table response between the rising and recession limbs. Thus the water table is a maximum of 50 cm higher during the recessions in comparison to the rising limbs for the same river stage, and frequently much less. The shape of the hysteresis curves, in terms of how open or closed they are, therefore approximates to how much water is stored temporarily within the floodplain over the course of a flood event (i.e., the bank storage effect).

[20] The water table of the inner floodplain of the spur transect (piezometers S2 and S3) responds in a somewhat similar fashion to river stage as do the river bank piezometers. The river water level determines the general envelope of the behavior of these piezometers since the hysteresis curve follows and includes the $x = y$ line. Since the rising limbs plot parallel to the $x = y$ line, this confirms that the water table responds synchronously to river stage changes

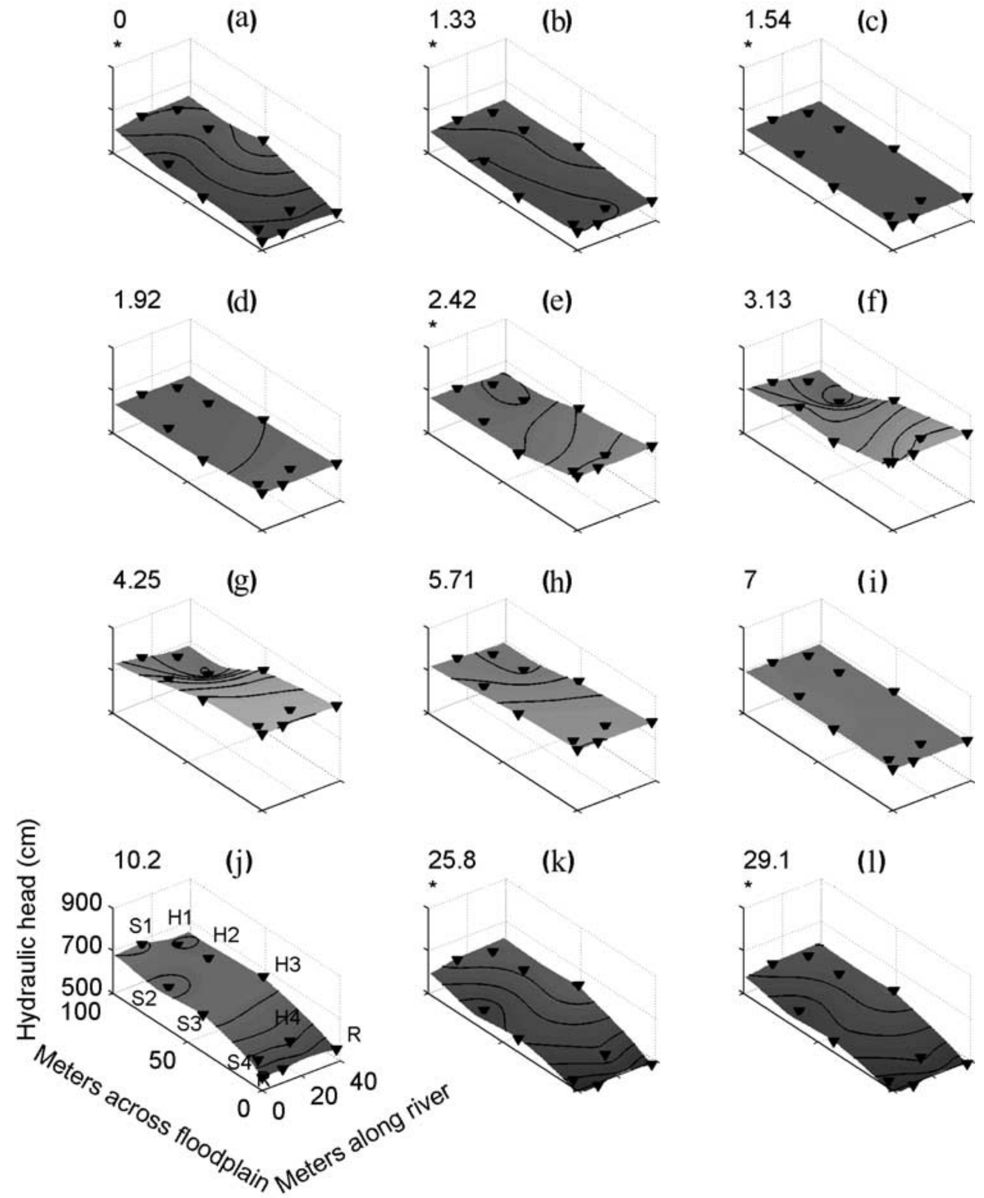


**Figure 6.** Same as Figure 5, but for February and March 1999.

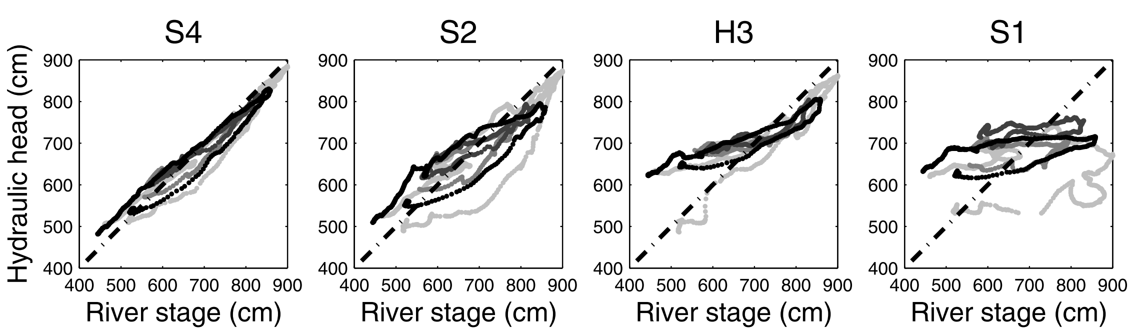


**Figure 7.** River stage–hydraulic head hysteresis plots for representative sensors, providing insights into the response of the water table to river stage within different floodplain units. The broken line gives the $y = x$ relationship (identical water table level). Data from all four over-bank (A, D, E, G) events are shown in chronological order from light gray to black. See text for further explanation.

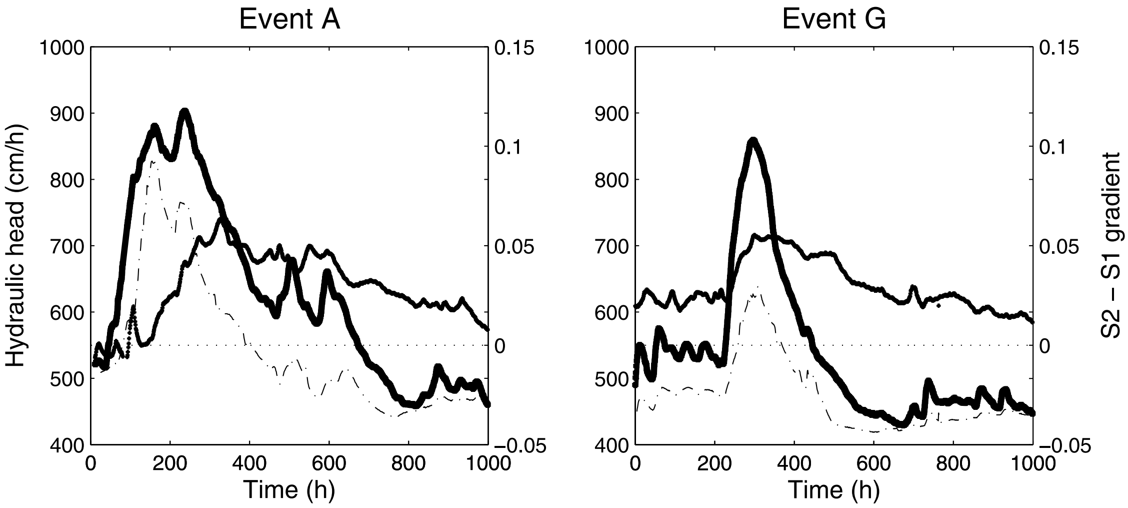


**Figure 8.** Change of the gradient from S2 to S1 (inclination of the groundwater ridge toward the hillslope) (dashed line) and the elevation of the water table at the back of the floodplain (S1) (thin black line) for events A and G over time. The river hydrograph is given in thick black. The dotted horizontal line ("no gradient") indicates the switch from a groundwater ridge situation (positive gradients) to base flow conditions (negative gradients). The gradient, approximating the relative magnitude of Darcian flow from the ridge to the hillslope, cannot explain the behavior of the water table at the hillslope-floodplain border.

and at approximately the same rate (~120–170 cm/day depending on the event), apart from an initial delay during the early rising period of the first autumn flood, event A. Again, the water table response during the recessions is more similar than during the rising limbs, since the data points of the recession periods plot more closely together. The hysteresis curves are relatively open, which means that the water table elevations for a given river stage are more different for these piezometers (S2 and S3) between the rising and recession limbs than for those in the in the near-channel area. At a given river stage, the water table may be up to 2 m higher during the recession than during the rising limb as is evident for event A, though these differences are smaller (~1 m and less) during the other events. This shows that water is stored for longer within the inner floodplain zone of the spur transect during flood events in contrast to the relatively limited storage within the river banks.

[21] The counterpart of S2 and S3, the hollow piezometer H3, shows a different behavior again. Except for the rising limb of event A, the response of H3 to river stage change is very similar for all rising and recession periods, as shown by the closed hysteresis loops. There is, hence, little retention capacity for flood water within the floodplain hollow. Prior to and after inundation at H3, the water level plots above river stage virtually all of the time, but still exhibits a trend following the river hydrograph, although with a lower rate of change (~60–90 cm/day depending on the event) than the river stage.

[22] The pattern of water table dynamics close to the hillslope-floodplain boundary (piezometers S1, H1, H2) is completely different to all other piezometers across the floodplain. Here, water tables show larger interevent differences and appear not to be related to river stage changes, exhibiting relatively small but rather complex fluctuations. Some regularity emerges since the water table dynamics also occupy a distinct area within the phase space (except for event A), and a roughly similar behavior of rising water tables around the flood peak shows up. However, the water tables rise by only 15–30 cm/day; this is much lower than the rate of rise of the river.

[23] While river stage is the primary driver of water table fluctuations for the river bank and spur transect groups of piezometers, whose water tables react instantly to river stage changes, a further factor is required to explain the water table fluctuations within the floodplain hollow and at the foot of the hillslope.

### 5.5. Hillslope-Floodplain Water Table Relationships

[24] We test the hypothesis that water table fluctuations at the hillslope-floodplain boundary are caused by the groundwater ridge, which drives water into this area. We then assess the relationship between the hillslope piezometers and the floodplain hollow piezometer H3 to clarify the role of hillslope runoff in influencing water table fluctuations within the floodplain hollow.

[25] River stage, the hillslope piezometer S1 and the gradient between S2 and S1, which approximates the inclination of the groundwater ridge toward the hillslope, are shown in Figure 8 for events A and G. Through event A, piezometer S1 indicates an increasing water table, independent from the inclination of the groundwater ridge, which peaks during the recession period while the gradient between S2 and S1 decreases, i.e., the groundwater ridge flattens. In contrast, during event G, S1 seems to rise synchronously to the change in gradient between S2 and S1, but the rising phase of S1 precedes the formation of a groundwater ridge, i.e., the water table at the floodplain-hillslope boundary starts to rise before a hydraulic gradient toward the hillslope becomes established, which could drive water into this area from the floodplain.

[26] The influence of hillslope runoff on water table fluctuations within the floodplain hollow at H3 is apparent in Figure 9. Except for the rising period of event A, the data points plot parallel to the S1 = H3 line, indicating that they are strongly correlated on an event basis. In contrast, H3's counterpart from the spur transect, S3, shows no consistent

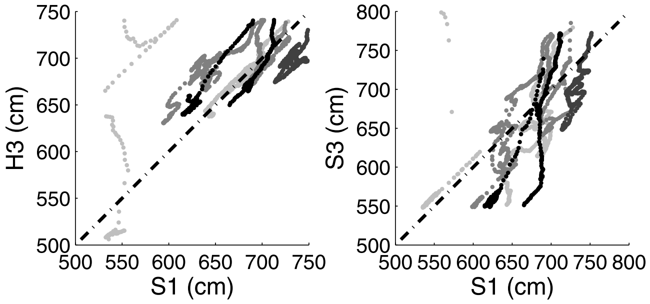


**Figure 9.** Water table elevation at H3 and S3 as a function of the hillslope piezometer S1. Only the period when the locations were not inundated during the rising and recession periods of all four over-bank (A, D, E, G) events are shown in chronological order from light gray to black. While the water table within the floodplain hollow (H3) follows the behavior of the water table of the hillslope piezometer (S1) during events (plotting parallel to the H3 = S1 line), no such relationship is evident along the spur transect.

relationship with S1, although short periods are evident that show linkages between them since the data plot parallel to the S1 = S3 line.

[27] Besides consistent dependencies between piezometers, and between piezometers and river stage, some relationships seem to emerge only on an event or subevent scale. The next section investigates whether water table fluctuations within the floodplain are subject to memory effects of previous events, by analyzing the response of the piezometers to river stage changes over the course of an event sequence (Events, B, C, D, E and F).

### 5.6. Water Table Fluctuations Over the Event Sequence

[28] Two main phenomena are apparent from Figure 10. First, except for the hillslope piezometers (S1, H1 and H2), the response of the floodplain water table shows few differences over the event sequence for all piezometers. While all other piezometers indicate a quick return to preevent levels, the hillslope piezometers clearly appear to be influenced by previous events and exhibit hysteresis behavior. Their water tables rise around the flood peak but thereafter maintain their level so that the water table progressively rises during the event sequence. Second, the relationship of the floodplain water table at the river banks and along the spur transect to river stage seems to strengthen over the event sequence, especially after the first over-bank event (event D). Although this effect is of secondary importance, it is suggested by the successive closer alignment of the data points along the $x = y$ line.

## 6. Discussion

[29] We propose a conceptual model that involves two interdependent mechanisms. First, kinematic waves induced by rapidly changing river stage cause floodplain water tables to respond quickly; and, second, the floodplain water table interferes with hillslope contributions that have to adapt to changing conditions of the hydraulic gradient field. First, we use the model to explain the system behavior over the course of a typical flood event. Then, we discuss factors that may be responsible for either recurrent or variable characteristics of water table response during flood events.

### 6.1. A Conceptual Model of Operating Mechanisms

#### 6.1.1. Rising Limb

[30] The rise of the river induces a kinematic wave that operates analogously to piston flow [e.g., *Anderson and Burt*, 1982] by pushing ‘‘old’’ floodplain water ahead and, hence, causes the river bank (H4, S4) and spur-floodplain water table (S3, S2) to rise near-synchronously and by the same amount. The hollow piezometer H3, although plotting above river stage and indicating the presence of hillslope runoff channeled through the hollow, also shows a rising water table but at a much lower rate. Because of decreasing hydraulic gradients, and hence decreasing fluxes toward the spur transect and the river, the water table at H3 will tend to rise as a result.

[31] Kinematic wave processes are well known in hydrology (see, for example, the review by *Singh* [2002]) and can be triggered by a rapidly rising river. There are several arguments that support the kinematic wave hypothesis here. First, flux velocities associated with Darcian flow are in the range of $10^{-4}$–$10^{-5}$ m h$^{-1}$ given a saturated hydraulic conductivity of $10^{-5}$–$10^{-6}$ m s$^{-1}$ at the field site and maximum water table gradients of only a few percent. These flow velocities are at least five to six orders of

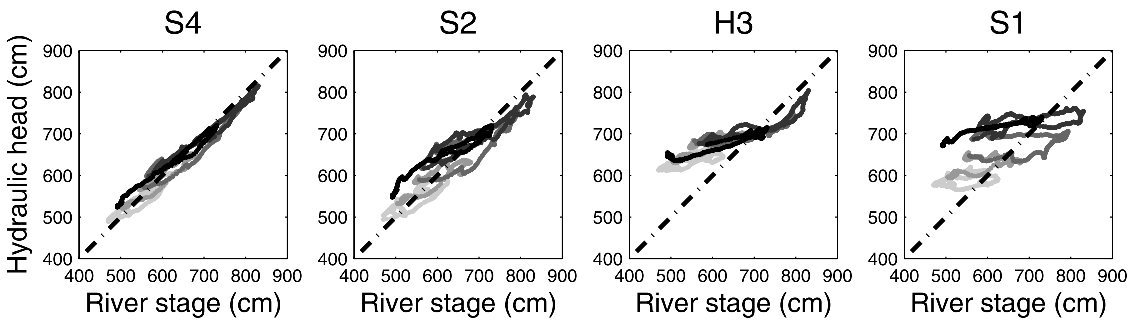


**Figure 10.** River stage–hydraulic head hysteresis plots for representative sensors (S4, S2, H3, S1) during the event sequence. The dash-dotted line gives the $y = x$ relationship (identical water table level). Data from events B, C, D, E, and F are shown in chronological order from light gray to black. Note the progressive rising of the water table at the hillslope sensor S1, while the water table responses at the river banks and spur transect tend to converge against the behavior of river stage as the sequence proceeds, indicated by a progressively closer alignment of the data points along the $y = x$ line.

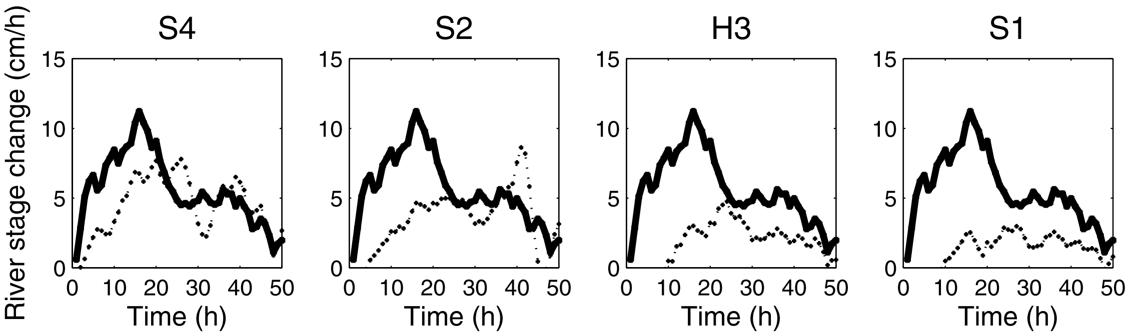


**Figure 11.** River stage change (thick black line) and water level change (dotted line) over time for representative sensors from a subset of the rising period of event G to illustrate the rapid, wave-like response of the water table to a period of rapid river stage changes. The rates of change were smoothed with a three-point moving average to remove some high-frequency noise.

magnitude too low to lead to mass transfer over the distances involved in the time available and cannot explain the strong relationship between piezometers and river behavior. Second, the response of the water table to the river stage during in-bank conditions is synchronous or nearly synchronous over ~70 m lateral distance of floodplain adjacent to the river channel and often associated with a rather planar rise of the water table. Thirdly, a wave-like response of the water table to a rapid increase in river stage is indicated in Figure 11. Here, the water table response to the impulse induced by the rapidly rising river is delayed by a few hours, which implies wave velocities of the order of meters or tens of meters per hour. This matches the order of magnitude of flux velocities that are required to explain the rapid response of the floodplain water table to river stage changes.

#### 6.1.2. Flood Peak

[32] The rising water tables at the hillslope-floodplain boundary around the flood peak are not caused by the groundwater ridge driving water into this area but result from the accumulation of hillslope water, which is dammed by the presence of the ridge. There are three main reasons to support this hypothesis. First, flux velocities are too low to explain the rising water tables. Second, if the water had originated from the groundwater ridge, the water table would fall just as quickly again after the disappearance of the ridge, which is not the case. Thirdly, we have already shown in section 5.5 that the water table at the hillslope-floodplain boundary starts to rise before the ridge exists. This interpretation is also supported by the tracer modeling study of *Claxton et al.* [2003] at this site.

[33] The development of a groundwater ridge has important implications since it temporarily prevents hillslope water from reaching the floodplain and thereby limits hillslope contributions to flood waves propagating downstream. A groundwater ridge will develop if the floodplain water table rises above the water table at the hillslope-floodplain boundary; its formation is therefore controlled by both river stage and hillslope runoff conditions. In summer and autumn when little or no hillslope runoff occurs and preevent floodplain water tables are low, a groundwater ridge may develop during in-bank events [*Burt et al.*, 2002b]. This is, however, unlikely to occur during the winter wet season, since hillslope discharge will sustain high water tables at the back of the floodplain; the typical base flow conditions associated with a weak hydraulic gradient toward the river will therefore tend to be maintained during in-bank winter flood events. On the basis of the presence or absence of a groundwater ridge, we calculate that hillslope discharge on to the floodplain was switched off for 28 days (~15% of the period studied) of the ~6 month winter flood season, with event A in October 1998 alone accounting for 14 days. Of course, switching off of hillslope contributions to the channel happens much more readily as soon as river stage exceeds the elevation of the floodplain water table, a condition that lasted for ~2 months (one-third of the period) during the 1998–1999 winter.

[34] Unfortunately, these findings cannot be regarded as being representative at the reach scale since *Stewart et al.* [1999] showed that considerable hillslope contributions enter the channel along this section of the river during flood events, which would be impossible if a groundwater ridge developed everywhere along the floodplain. Hydrological short circuiting between hillslope and river can occur when the floodplain is close to adjoining hillslopes, or as a result of agricultural drainage. In this respect, areas at the back of the floodplain where the occurrence of short circuiting is likely deserve particular attention for land use and flood prevention management.

#### 6.1.3. Recession Limb

[35] Given that floodplain water tables immediately follow the declining river stage, the same kinematic process is likely to operate as during the rising period but in the opposite direction, i.e., water drains out of the floodplain instead of being pushed in. The recession period typically goes through a transition from a nearly horizontal water table to a horizontal water table at the back of the floodplain with lateral gradients to the river in the near-channel area, to a fully three-dimensional pattern caused by high water tables in the floodplain hollow related to hillslope runoff. The persistence of the groundwater dome within the floodplain hollow throughout the winter season during low river discharge is largely an effect of low Darcian flow velocities within the floodplain.

### 6.2. Recurring Patterns and Interevent Differences

[36] Considering the factors that control or influence floodplain water table behavior during flood events, two

groups can be distinguished. First, factors that can be assumed to be constant, which change only on timescales of landscape evolution. Among these are the morphology of the floodplain and adjacent hillslopes, the sedimentary architecture and material properties, including the connectivity between channel and alluvial aquifer. These have crucial importance for water table dynamics by determining inundation patterns, hillslope runoff inputs and preferential flow paths (PFPs). These factors provide the framework within which water table fluctuations take place, confine the system behavior into a distinct region of possible system states and, hence, produce recurring patterns of water table response. In this respect, we have recognized several distinctive patterns of water table response at the study site. First, we identified a group of piezometers near the river bank (S4, H4) and a group further away from the river along the spur transect (S3, S2), which are strongly controlled by river stage alone. This cannot be simply explained by the distance to the river since, for example, S2 is more strongly correlated with river stage than S3, despite being 30 m further away from the river with a 0.8 m higher. This effect was previously recognized by *Burt et al.* [2002b] who speculated about the influence of possible buried channel features at the site which might act as PFPs. Second, we recognized a group of piezometers at the back of the floodplain (S1, H1 and H2) whose behavior reflects hillslope runoff inputs on the one hand and an accumulation effect of hillslope water on the other, the latter becoming significant during periods of elevated floodplain water tables that slow or even dam the flux toward the river. This accumulation effect also characterizes the behavior of the piezometer H3 within the floodplain hollow that serves as conduit of hillslope discharge. Although the water table at H3 remains higher than river stage until the location gets inundated, the water table at H3 rises slowly when the river rises because this prevents water discharging from the floodplain to the river. Hence hillslope water accumulates within the floodplain hollow during the rising limbs of events which causes the water table there to rise.

[37] In conclusion, different mechanisms act and interact at different locations within the floodplain which are stable over time and reproduce typical sequences of water table morphologies over the course of flood events. However, some differences of water table response and water table appearance can be identified between events which are attributed to the second group of factors that influence floodplain water table fluctuations.

[38] Factors influencing water table fluctuations which are subject to short-term variations can alter the system behavior within the space given by morphological and sedimentary controls, and are therefore the reason for patterns deviating between events. The shape and magnitude of the river hydrograph is clearly most important since river stage changes drive floodplain water table fluctuations during events as shown previously. Varying hillslope inputs as a function of local rainfall and antecedent conditions may interfere with the river-controlled water table patterns, especially in the near-hillslope area and along particular morphological features such as the floodplain hollow at this field site. However, water table response to hillslope inputs and river stage changes is highly dependent on moisture conditions in the unsaturated zone, as shown by several lines of evidence. First, the recession periods seem always to be characterized by similar patterns of water table behavior when the floodplain is extensively saturated. By contrast, interevent differences are most pronounced during rising periods where antecedent conditions may well be different. Second, over the course of the event sequence, the piezometers that behave according to the river water level showed better connectivity to the river once the floodplain had been inundated during the first over-bank event in December 1998 (event D). Water tables responded quicker to river stage changes, following closely the $y = x$ function graph during the subsequent events E and F. Third, the pattern of water table response during the rising period of event A in autumn 1998 is different to all subsequent events because the floodplain was dry prior to the first out-of-bank event, as indicated by a low, horizontal prestorm water table, no sign of hillslope runoff and no elevated river levels in the preceding period. This suggests a critical role for the preevent condition of the unsaturated zone and the capillary fringe in determining water table response.

[39] Contrasting antecedent moisture conditions in conjunction with the initial absence of hillslope discharge are likely to be responsible for the discrepancy between the pattern of event A and those that followed. The system undergoes a rapid transition from the dry "summer mode" without continuous hillslope fluxes to the wet "winter mode" with sustained hillslope discharge during event A. A wet floodplain with high soil moisture content is typical for the winter season at this field site [*Claxton et al.*, 2003] and may assist in generating a rapid water table rise with recurring characteristics, as is evident for all events considered except event A. These findings are in accordance with the reach-scale water balance modeling study of *Stewart et al.* [1999] who also identified distinct behavior during the first flood event of 1993–1994 winter season. *Stewart et al.* [1999] assessed inflows and outflows to a 40 km reach of the Severn between the gauging stations at Montford Bridge and Buildwas, which are upstream and downstream respectively of the Leighton field site. To do this, *Stewart et al.* [1999] analyzed gauged main stem and tributary flows, and supplemented this with hydrological models of the ungauged tributaries and hillslopes adjacent to the floodplain in order to close the floodplain water mass balance. The first winter event was found to be the only one of the whole 1993–1994 flood season where the outflow discharge from the reach at Buildwas was lagged and attenuated compared to the sum of all inflows. For all other events up to 20% more water was gauged at Buildwas than was gauged entering the reach.

## 7. Summary and Conclusions

[40] We have identified and discussed patterns of floodplain water table fluctuations during flood events of the winter season 1998–1999 within a lowland reach of the River Severn, England. These patterns have three-dimensional characteristics and reveal clear spatial and temporal regularity. We attribute the constancy of patterns to sedimentary and morphological controls on the floodplain and adjoining hillslopes. Spatially, we have identified areas within the floodplain of similar water table response, some

closely related to river stage changes while others are slope controlled. Temporally, the pattern of water table fluctuation over the course of a flood event is essentially repetitive for comparable river hydrographs. Deviations are caused by low antecedent soil moisture, which can slow water table response significantly and induce irregularity. This is the case for early autumn events, when the capillary fringe is initially underdeveloped but during which the catchment and the floodplain undergo a wetting-up transition with implications for the water table response and the propagation of flood waves downstream during later events [see *Stewart et al.*, 1999].

[41] We have proposed a conceptual, three-dimensional model of floodplain water table response, which incorporates a piston flow process due to rapidly rising river water levels and the impact of hillslope contributions to the floodplain. The former process can be interpreted as a kinematic wave, where river water entering the floodplain through the river banks pushes older floodplain water ahead of it and causes a rapid water table response over many tens of meters across the floodplain, a response that cannot be accomplished by Darcian flow alone. The development of a groundwater ridge at the time of the flood peak dams hillslope inputs and forces the water table at the floodplain-hillslope boundary to rise. During the recession limb, and low-flow conditions in general, hillslope discharge along a hillslope hollow causes localized elevated water levels and three-dimensional flow patterns within the floodplain.

[42] A thorough test of our model will require a series of careful tracer experiments to determine source, path, and velocity of flow within the floodplain and its extension to other sites to determine its wider relevance. We believe the processes identified will generally apply to river-floodplain systems with perennial discharge and a good connection between river and floodplain aquifer. However, the interactions between hillslope runoff and the spatial response patterns on the floodplain are obviously site-specific, controlled by local topography and sedimentary architecture. Nevertheless, the geomorphology of our study site (wide floodplains bounded by much steeper hillslopes) is typical of many European river corridors. In summary, we believe the processes we have identified will be common for this class of system but may find subtly different expression depending on the exact geomorphological and climatic setting.

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